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Quantified biotic and abiotic responses to multiple stress in freshwater, marine and ground waters

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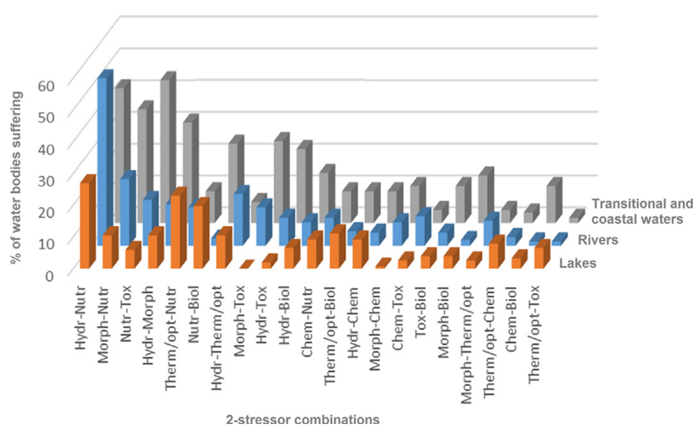
HIGHLIGHTS

- We reviewed 219 papers quantifying effects of multiple stresses on aquatic systems.
- Nutrient stress occurred in 71% to 98% of multi-stress situations in surface waters.
- Hydromorphological stress alters the nutrient stress sensitivity of water bodies.
- R^2 of stress-effect models using fish increased under multi-stress conditions.
- R^2 of benthic flora dropped with multiple stressors involved.

GRAPHICAL ABSTRACT



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ABSTRACT

We reviewed 219 papers and built an inventory of 532 items of ecological evidence on multiple stressor impacts in rivers, lakes, transitional and coastal waters, as well as groundwaters. Our review revealed that, despite the existence of a huge conceptual knowledge base in aquatic ecology, few studies actually provide quantitative evidence on multi-stress effects. Nutrient stress was involved in 71% to 98% of multi-stress situations in the three types of surface water environments, and in 42% of those in groundwaters. However, their impact manifested differently along the groundwater–river–lake–transitional–coastal continuum, mainly determined by the different hydro-morphological features of these ecosystems. The reviewed papers addressed two-stressor combinations most frequently (42%), corresponding with the actual status-quo of pressures acting on European surface waters as reported by the Member States in the WISE WFD Database (EEA, 2015). Across all biological groups analysed, higher explanatory power of the stress-effect models was discernible for lakes under multi-stressor compared to single stressor conditions, but generally lower for coastal and transitional waters. Across all aquatic environments, the explanatory power of stress-effect models for fish increased when

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multi-stressor conditions were taken into account in the analysis, qualifying this organism group as a useful indicator of multi-stress effects. In contrast, the explanatory power of models using benthic flora decreased under conditions of multiple stress.

1. Introduction

In our globalizing world, multiple stresses on surface and groundwater systems from natural and man-made disturbances have become the rule rather than an exception. A stressor can be either an abiotic as well as a biotic factor (Cottingham, 1999; Vinebrooke et al., 2004) that exceeds its range of normal variation and affects individual physiology, population performance or community balance in a significant way. Similarly, most other definitions of ecological stress (e.g., Barrett et al., 1976; Auerbach, 1981; Underwood, 1989; Hughes and Connell, 1999) include the effects at individual and demographic (population or functional group) levels. At the individual level, stress is considered as a sub-lethal effect on the physiology of an organism, e.g., a decline in feeding, growth, or fecundity, or a biochemical change. At the community or ecosystem level, stress denotes an acute or chronic disturbance that causes a decline in the number of organisms affecting biotic interactions and integrity (e.g., Hyland et al., 2003; Pilière et al., 2014).

Ecosystems as dynamic and self-organizing systems are continuously adapting to a multitude of disturbances (Connell, 1978). Rapid increase in anthropogenic pressures has modified the types, frequency and magnitude of disturbances. Some species cannot keep up with these changed disturbance regimes, while others take advantage of the freed-up or new resources (Halpern et al., 2008). At any organizational level, multiple stress situations include biological interactions (e.g., food chain interactions, resource competition), human pressures (which typically alter more than one environmental factor), and impacts of climate change (Ormerod et al., 2010).

A number of theoretical concepts in the field of multiple stressor research underpin on-going research activities on multi-stressor effects. The landscape filter concept (Tonn et al., 1990) explains the structure of river communities as a result of a set of environmental constraints filtering species that can be found at a place. The species co-tolerance model (Vinebrooke et al., 2004) hypothesizes that positive correlation of tolerance of species to multiple stressors increases ecosystem resistance, while negatively correlating tolerance results in additive or synergistic impacts, compared to situations where tolerances of each species are randomly distributed. The related stress-gradient hypothesis highlights a global shift towards positive species interactions with increasing environmental stress. So far, the latter has been tested mostly on vascular plants (He et al., 2013). The 'control species' concept (Downes, 2010) advocates measuring the reaction of a group of 'treatment species', which are predicted to respond to a specific gradient against that of 'control species' not sensitive to the stressor of interest because of specific features of their biology or ecology. Simulating in this way the experimental conditions in field situations has a potential to improve our capacity to draw conclusions about causality.

The common analytical approach in multi-stress studies has been to disentangle the effects of confounding factors one-by-one (e.g., Vonesh et al., 2009; Battarbee et al., 2012) and specify the cause–effect chains underlying these relationships. This requires careful hypothesis-driven research, often combining field studies with experiments and modelling, to discover the intimate linkages between species and/or functional groups and their environment (Downes, 2010; Ormerod et al., 2010). By now, this massive and continuing effort has revealed: (i) a huge variation in impact–response relationships across different aquatic environments (Verdonschot et al., 2013), seasons (Lytle and Poff, 2004), climatic regions (Wasson et al., 2010), and biotic communities (Johnson et al., 2006); (ii) a domination of non-linear and often lagged responses in biotic reactions to stressors (Dodds et al., 2010); (iii) dependence of a particular stress effect with perturbation history (Hughes and Connell, 1999); and (iv) stressor's interactions amplifying or dampening each-other's effects (Folt et al., 1999; Micheli et al., 2013).

Against this background it seems rather obvious that multiple stressors pose specific challenges for aquatic ecosystem management (Hering et al., 2015). Practical knowledge is urgently required not only on the additive effects of multiple stressors (implying that management addressing the largest stressor will have the greatest benefit), but also on their interacting effects, because future rates of ecosystem decline predicted on the basis of individual stressor effects will be underestimated (Brown et al., 2013). However, current management practice generally does not integrate scientific evidence on multi-stressor effects. The main aim of this review is thus to assess the quantity and quality of the scientific evidence base on multiple stress effects in aquatic ecosystems including rivers, lakes, transitional and coastal (TraC) waters, and groundwaters. In particular, we address the following questions:

- Which stressor combinations are commonly documented in scientific literature?
- How strong are these effects across different aquatic environments and biological response variables?
- How reliable is this evidence with regard to the underlying data quality?
- How common are non-additive, i.e., synergistic and antagonistic effects?

The collated evidence is intended to provide a fundamental contribution to the design of a diagnostic tool supporting multi-stressor management in aquatic systems under the European Water Framework Directive (WFD). We expected to find knowledge gaps, i.e., multi-stress situations for which conceptual knowledge exists but the effects are not quantified. We also hypothesized that the same drivers are responsible for the dominating stressor combinations in all aquatic environments, but that the responses differ between those due to diverging sensitivity. Finally, we questioned whether the different research traditions in rivers, lakes, and TraC waters are reflected in the methodological approaches used in multi-stressor studies.

2. Material and methods

2.1. Literature selection

For the literature survey, we used the ISI Web of Science citation databases (see Sheet 1 in the Supplementary Materials [SM] for the combination of search terms used in the queries). Although zooplankton is not a mandatory biological group for the WFD, it was included as a search string for lakes because the central position of zooplankton in lake food webs renders a high indicative value to it in multi-stress situations (Altshuler et al., 2011; Jeppesen et al., 2011). Since the aim was to find papers in which the multiple stress effects were quantitatively described, we screened the retrieved papers for that. The search was extended by a 'snowball' approach looking through the references in relevant papers. We excluded ecotoxicological lab experiments with single species as test organisms, or bioassays done only with natural stressors (e.g., Przeslawski et al., 2015).

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